Optical networks' topologies: costs, routing and wavelength assignment

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Abstract. Optical technology is the principal component of nowadays backbone networks and the whole Internet. The technological developments that paved the way for switching in the optical domain introduced many challenges, such as lightpath topology design, lightpath routing and network-wide spectrum allocation. The solutions to these problems are highly affected by the underlying network topology. Therefore, we study the effects of the fiber network topology on the static routing and wavelength assignment (RWA) as well as the capital expenditures (CAPEX) using several spatial network models, which resemble real network topologies, including networks with complex structures.

Keywords: Optical networks, WDM systems, RWA, Spatial networks

1 Introduction

Optical technology is the core of the Internet backbone today and will most likely remain its principle part for a long time. Wavelength division multiplexing (WDM) systems using erbium doped fiber amplifiers was a cornerstone technology in optical networking [1], while other new technologies are being continuously developed. The introduction of switching in the optical domain opened the possibility of end-to-end optical networking, which circumvents the optical-electrical-optical conversion at each node. A broad overview of the challenges and the developments in optical networks is given in [2].

One of the central problems in optical networks is routing and wavelength assignment (RWA), where the challenge is to find routes and assign wavelengths for a given set of connection requests (lightpaths), such that the number of wavelengths on each link is minimal. This problem has been extensively studied and is surveyed in [3]. RWA is an optimization problem that can be solved either exactly for small sized networks, or it can be addressed with some approximative approach for larger networks. The problem can be either set in a static environment where connection requests are known in advance, or in a dynamic environment where connection requests arrive dynamically. Sometimes it is a combination of an initial solution for a given network and dynamically supporting new traffic.

Another important aspect in optical networking is the network topology, both the optical fiber cables layout, as well as the virtual lightpath topology on top of it [4]. The effects of the physical network layout on its availability have been examined in [5] using the same network models that we consider in this paper.

Standard WDM systems employ on-off keying and fixed wavelength grid, however, the continuous rise of the required bandwidth has led to the development of elastic optical networks with more complicated modulation schemes such as orthogonal frequency division multiplexing (OFDM) and flex-grid spectrum allocation [6]. With OFDM we can achieve finer granularity by allowing flexible bandwidth allocation. In flex-grid networks RWA is substituted with the routing and spectrum allocation (RSA) problem [7, 8]. Our analysis of the effects of network topology are presented for the standard fixed-grid WDM networks, nevertheless, the general conclusions would also hold for flex-grid networks.

In this paper, we examine the effects of the underlying physical topology, while for the lightpath topology we randomly generate a certain number of connections from each node. The different network topologies are compared in terms of the solutions to the static routing and wavelength assignment problems as well as their capital expenditures (implementation costs). We split the RWA into two subproblems: routing and wavelength assignment. The routing is set as an integer linear program (ILP), which is solvable exaclty in a reasonable amount of time for the networks' size considered here, while the wavelength assignment is reduced to graph-coloring. The relationship between the physical and the virtual topology is also an important issue, however, we leave it for our future work.

The paper is organized in the following way. In Section 2, we describe several spatial network topologies, while the standard RWA problem is shown in Section 3. In Section 4 we present the equations used for the network costs calculations. The setup for the numerical simulations and the results obtained in our study are given in Section 5, while Section 6 concludes the paper.

2 Network Topology Models

The static routing and wavelength assignment problem and its implementation cost is studied on several network models, such as Random Geometric Graph (RGG) [9], Gabriel Graph (GG) [10], Relative Neighborhood Graph (RNG) [11], K-Nearest Neighbor Graph (K-NNG) [12], Waxman Graph (WG) [13] and Spatial Barabási Albert Graph (SBAG), similar to the work presented in [14, 15]. The number of nodes and their 2D position in the network topology is fixed, whereas the links are generated according to one of the above-mentioned models. These models simplify the real optical network structure and do not consider all of the design objectives of the physical optical network, however, they represent the main properties of real optical networks and allow us a deeper insights into the RWA problem. In the following we will explain all the network models, while their particulate instances used in our simulations and their graphical representation is demonstrated in Section 5.

Random Geometric Graph model (RGG) – This is a geometric alternative of the Erdős Rényi random graph, where N nodes are scattered on a 2-dimensional unit square, according to an uniform distribution. Two nodes i and j are connected only if their Euclidean distance $d(i, j) \leq r$, where r is a given distance threshold, which is inversely proportional to the link density in the obtained graph. A variation of this model is used in [16] for modeling sensor network with optical links.

Gabriel Graph (GG) – The Gabriel Graph [10] models the optical network as a grid-like structure and because of this property closely matches American telecommunication networks, such as AT&T, Level 3 and Sprint. In this model a link is formed between any two nodes i and j only if $d(i, j)^2 \leq d(i, k)^2 + d(j, k)^2$, where k is any other node in the graph. Compared to RGG it does not have an explicit parameter with which we can control the number of links. However, one can tune the number of links by not taking into consideration the inequality for some of the node pairs. In addition, this model shows smaller cost compared to other graph models [17].

Relative Neighborhood Graph (RNG) – Compared to GG, in this model a link is formed only if there is no other node k that is closer to both i and j than they are to each other or $d(i, j) \leq \max\{d(i, k), d(j, k)\}$ [11]. This is a more restrictive condition for link forming and here again one can use the same relaxation as in the GG model in order to control the number of links. However, in this work we implement both models (GG and RNG) with the strong inequality for any node pair.

K-Nearest Neighbor Graph (K-NNG) – In this model, each node i has links to a set of k nodes closest to it, called its k-nearests neighbors [12].

Waxman Graph (WG) – In this probabilistic model, the nodes are unformly distributed on a unit square and any two nodes i and j are connected according to a geographic-based probability $P(i, j) = \alpha \exp^{-d(i,j)/(\beta L)}$, where L is the maximum distance between any two nodes. The link density in the obtained network is proportional to the constant $\alpha \in (0, 1]$. Moreover, using the parameter $\beta \in (0, 1]$ we can control the number of long-distance links, which makes this model tunable and more realistic for optical network topology [13].

Spatial Barabási Albert Graph (SBAG) – The Barabási Albert model produces scale-free graphs, by incorporating two realistic mechanisms, growth and preferential attachment. The models starts with a small initial 'seed' network, and then new nodes emerge with time (growth). Each new node connects by m new links with a higher probability to existing nodes having more neighbors (preferential attachment). The model used in this work adds a spatial dimension in a scale-free graph, where besides the growth and the preferential attachment mechanism in the Barabási-Albert model [18], the new node forms a link to an existing one with a probability that is inversely proportional on their distance, i.e. $P(i, j) = k_j/(d(i, j)^\alpha \sum_j k_j)$ where k is the degree of the node, d is the Euclidean distance. Here again, as in the WG we can control the distance effect using the parameter $\alpha \geq 0$. This model produces network where small number of nodes have many connections, also known as hubs, while the rest of the nodes have only few connections. It is known that the Internet as a whole has such a structure, furthermore, some backbone optical networks, for example in England, are also known to have this type of structure.

3 Routing And Wavelength Assignment

The routing and wavelength assignment (RWA) problem in WDM optical networks can be described as finding a route from a source node to a destination node for a given set of optical connection requests (lightpaths) between node pairs and assigning wavelengths to these routes. This paper focuses on the static RWA problem, assuming all required lightpaths are known in advance. Since these connections are assumed to remain in place for relatively long periods of time, it is worthwhile to attempt to optimize the way in which network resources (e.g., physical links and wavelengths) are assigned to each connection. The number of wavelengths that can be used on a single fiber is limited and depends on the frequency bands used and the channel spacing. Therefore, the goal of the RWA algorithms is finding routes that minimize the number of unique wavelengths used in the network, thus, minimizing the blocking probability. The RWA problem can be partitioned into two subproblems: (i) routing and (ii) wavelength assignment, and each subproblem can be solved separately. Although, such a solution could be suboptimal, the problem becomes easier. The routing problem is NP-hard and can be formulated as an integer linear program (ILP). We solve the routing problem using the Gurobi solver [19].

3.1 Routing Subproblem

In order to establish a lightpath between a source node s and a destination node d, one needs to determine the path (route) from the source to the destination. The precondition to solve the routing problem requires previous knowledge of the network topology (nodes and physical links between nodes) and a connection requests list that is used to create a traffic matrix λ_{sd}. As defined in [20], the ILP formulation can be written as

Minimize

$$F_{\max}, \tag{1}$$

such that

$$\lambda_{sd} \in \{0,1\}, \tag{2}$$

$$F_{\max} \geq \sum_{s,d} F_{ij}^{sd} \; \forall ij, \tag{3}$$

$$F_{ij}^{sd} \in \{0,1\}, \tag{4}$$

$$\sum_{i} F_{ij}^{sd} - \sum_{k} F_{jk}^{sd} = \begin{cases} -\lambda_{sd} & \text{if } s = j \\ \lambda_{sd} & \text{if } d = j \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

The traffic matrix λ_{sd} defined in Eq. (2) uses binary values indicating whether there is a lightpath from a source to a destination node, i.e. the elements have value one if there is a lightpath between two nodes and zero otherwise. Later on we create a matrix F^{sd} for every connection. The matrix elements F_{ij}^{sd} get a value one if there is an assigned path on the physical link between nodes i and j for the connection 'sd', and is zero otherwise. Eq. (5) describes the network flow conservation, i.e. the total flow entering a node must equal the total flow leaving the node. Finally, after all restrictions are taken into consideration, $F_{\max}$ takes the value of the maximum sum from all F^{sd} matrices.

3.2 Wavelength Assignment Subproblem

Once the routing algorithm sets up the path for each connection, the number of lightpaths at each physical link depends on the number of different connections that pass through. If there are more than one lightpaths sharing the same physical link, then different wavelengths must be assigned to them. If the network does not have a wavelength conversion at the intermediate switches, the lightpath must have the same wavelength throughout its path which is known as the wavelength continuity constraint. Assigning wavelength colors to different lightpaths is achieved by using a graph-coloring algorithm. The algorithm's objective is to minimize the number of wavelengths. This algorithm uses a coloring graph where each node represents one point-to-point connection. The connections that share some common link are neighbors in the coloring graph. If two nodes are connected by an edge, they must be colored with a different color. The nodes of the graph must be colored so that each node is assigned to the first color not used by any of its adjacent nodes. In this way we minimize the total number of colors used. Once the graph coloring problem is solved, the color associated with each node in the graph represents the wavelength to be assigned.

4 Cost Calculations

In this section we address the problem of calculating the physical topology capital expenditure (CAPEX) with given node locations and a traffic matrix. We follow the simple procedure presented in [21], while for more detailed cost calculations the reader can refer to [22]. The costs of an optical network Capital Expenditure (CAPEX) components include fiber, optical amplifier (OA), OXC (Base), transponder and trunk card (WSS). The CAPEX can be divided into costs at the optical nodes and costs related to the fiber links.

The optical node cost is a sum of the base cost, interfaces and transponder costs. The base cost (C_{Base}) is actually the OXC cost. The optical interface costs come from the price per WDM trunk card (C_{Trunk}) and the node's degree d_n. The transponder costs are the price per optical transponder ($C_{\text{Transponder}}$) multiplied by p_n – the maximum number of optical connections that will begin or end at node n. Now the cost of the optical node n can be computed as

$$C_{\text{Base}} + d_n C_{\text{Trunk}} + p_n C_{\text{Transponder}}. \tag{6}$$

The cost of a link includes the optical fiber cost and optical amplifiers' cost. The optical fiber cost is the product of the fiber cost per km (C_{FO}) and the fiber length of link l in km (F_l). On the other hand, the cost of the optical amplifiers and other components like dispersion compensators, is a floor function of the link length divided by the amplifier span (S) and multiplied by the costs of one group of those components C_{OA}. Thus, the cost of the optical link l becomes

$$F_l C_{\mathrm{FO}} + \lfloor \frac{F_l}{S} \rfloor C_{\mathrm{OA}}. \tag{7}$$

The total CAPEX in a network of N nodes and L links can be calculates as

$$\begin{aligned} \mathrm{CAPEX} = & \sum_{n=1}^{N} (C_{\mathrm{Base}} + d_n C_{\mathrm{Trunk}} + p_n C_{\mathrm{Transponder}}) \\ & + \sum_{l=1}^{L} (F_l C_{\mathrm{FO}} + \lfloor \frac{F_l}{S} \rfloor C_{\mathrm{OA}}). \end{aligned} \tag{8}$$

5 Results

Let us examine the routing and wavelength assignment in the previously described topology models. All graphs are generated with $N = 100$ nodes at the same position for every model and the number of links per graph are given in Table 1d. RGG is generated with a distance threshold $r = 450$, while in KNNG we use $k = 5$ nearest neighbors. In WG we set $\alpha = 0.7$ and $\beta = 0.11$, while in SBAG we use $m = 4$ and an initial seed network of four nodes and four links. We have used $N_C \in \{100, 200, 300, 400, 500\}$ connection requests, with N_C/N connections drawn randomly from each node. The path for each pair (s, d) in the connection request list found such that $F_{\max}$ is minimal, and the results for the different models are shown in Fig. 2a. $F_{\max}$ increases with the number of connections for every model. The SBAG model has the lowest $F_{\max}$ and RNG has the highest. Consequently, the number of wavelengths for routing the same connections in SBAG is the smallest and in RNG is the largest. Fig. 2 shows that for WG, $F_{\max}$ is also small and close to the one in SBAG. On the other hand, the number of wavelengths for the RGG, GG and KNNG are close to each other, as well as $F_{\max}$. However, the difference between the number of wavelengths in RGG compared to GG and KNNG is growing less than the difference in $F_{\max}$.

In order to compare the implementation costs for the different models we use the costs of the individual network components given in Table 1. The sum of all optical links cost per model is shown in the Table 1b, calculated using Eq. 7. Table 1a shows the total nodes cost per model for different N_C, calculated using Eq. 6. Finally, the total implementation cost (CAPEX) in Table 1c represent sum of 1a and 1b, and it is calculated by Eq.8. From the obtained results we conclude that implementing the RNG model is cheapest, while implementing the WG model is the most expensive in the considered setting. Comparing the SBAG, WG, KNNG and RGG models, we can see that they all have similar links number, but the SBAG and WG models have higher cost compared to the KNNG and RGG models as a consequence of the larger number of long links. On the other side, the number of wavelengths is drastically lower in the SBAG and WG models, which allows larger number of connections. If we compare SBAG and WG, we can say that SBAG is better as it has both lower $F_{\max}$ and smaller CAPEX. Similarly, considering that the implementation of the RGG and GG models are similar with each other according to the spatial distribution, we can say that the GG model implementation is a better choice, because it has smaller $F_{\max}$ and CAPEX.

The results provide a comparative analysis of networks with different topologies that can be used to analyze the existing networks as well as to be taken into consideration in the development of new networks.

Table 1: (a-c) Implementation costs in €1k (€1000) of different network models with different number of connection requests N_C. The cost for optical fiber per kilometer is €1k, OXC (BASE) cost is €200k, cost per transponder is €3k, trunk card (WSS) cost is €20k and the cost per optical amplifier (needed at every 80 km) is €8k. (d) Number of links (L) in each graph.

(a) Nodes cost

	N_C				
Model	100	200	300	400	500
RGG	32720	33320	33920	34520	35120
GG	27920	28520	29120	29720	30320
RNG	25320	25920	26520	27120	27720
KNNG	32480	33080	33680	34280	34880
WG	32400	33000	33600	34200	34800
SBAG	32320	32920	33520	34120	34720

(b) Links cost

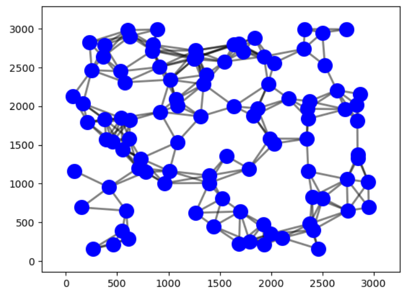
	N_C
Model	100-500
RGG	100791
GG	58376
RNG	30438
KNNG	102094
WG	220940
SABG	168196

(c) CAPEX

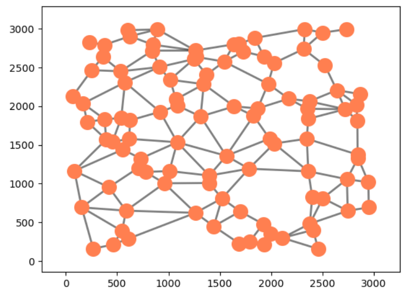
	N_C				
Model	100	200	300	400	500
RGG	133511	134111	134711	135311	135911
GG	86296	86896	87496	88096	88696
RNG	55758	56358	56958	57558	58158
KNNG	134574	135174	135774	136374	136974
WG	253340	253940	254540	255140	255740
SBAG	200516	201116	201716	202316	202916

(d) #Links

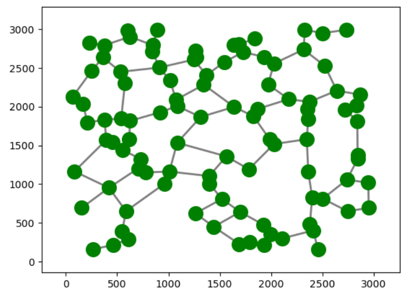
Model	L
RGG	303
GG	183
RNG	118
KNNG	297
WG	295
SABG	293



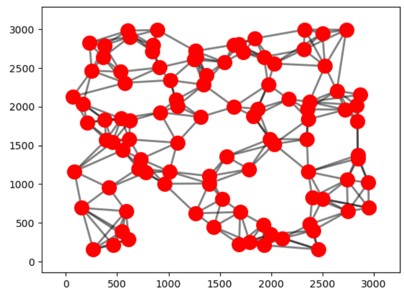
(a) Random Geometric Graph



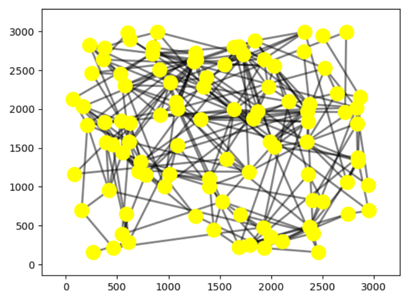
(b) Gabriel Graph



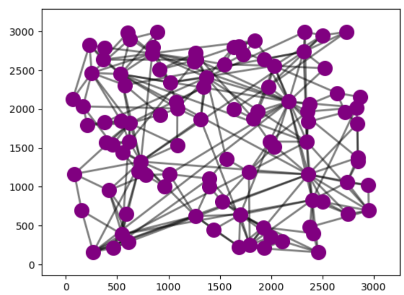
(c) Relative Neighborhood Graph



(d) K-Nearest Neighbor Graph

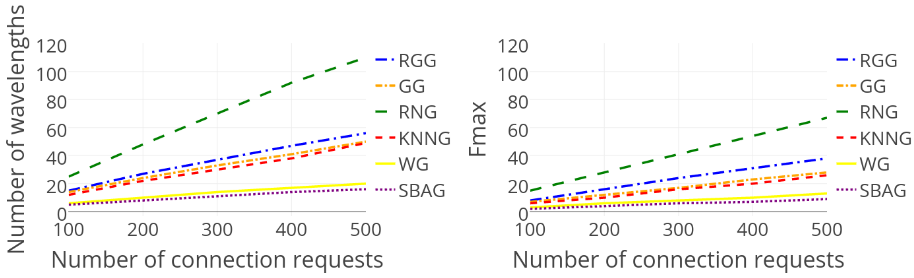


(e) Waxman Graph



(f) Spatial Barabasi Albert Graph

Fig. 1: Several network topologies with 100 nodes randomly placed in an area of 3000×3000 km^2 (nodes' positions are equal in all networks), and links generated according to the corresponding model.



(a) (b)

Fig. 2: Comparison of $F_{\max}$ (maximal number of wavelengths per link) and Number of wavelengths (unique number of wavelengths in the network) for RGG, GG, RNG, KNNG, WG and SBAG models with different connection requests.

6 Conclusion

This paper addresses the problems of traffic routing, wavelength assignment and capital expenditures in a direction of comparing optical networks with different physical topologies. Using numerical simulations we characterized the main properties of the considered topologies. While some topologies require lower implementation costs, other require fewer number of wavelengths, thus allowing more concurrent connections. According to the results we may say that there is no ideal topology, however, SBAG and GG proved better than their similar alternatives. Depending on the available resources, the physical limitations and the requirements, we could determine which model is more appropriate.

As a future related work, one can study the relationship between the physical fiber topology, the virtual lightpath topology and the traffic patterns. The same physical topology models as here could be used, while it can be experimented with the traffic patterns and the virtual topology.

7 Acknowledgment

This research was partially supported by the Faculty of Computer Science and Engineering at Ss Cyril and Methodius University in Skopje, Macedonia.

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